



The Search for $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ and $K_L \rightarrow \pi^0 \mu^+ \mu^-$

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Table of Contents

- 1) Introduction and Motivation for Studying $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$
(note: $K_L \rightarrow \pi^0 \mu^+ \mu^-$ is being studied as a secondary analysis)
- 2) Previous KTeV Studies and Results
- 3) $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Event Reconstruction
- 4) Results from Crunch Procedure
- 5) Normalization Mode Studies
- 6) Conclusions

Introduction & Motivation

- a preliminary KTeV study on $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ was performed in late 2005.
- currently, there's no published calculation inside the Standard Model for $Br(K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-)$, although the decay is possible via γ^* .
- however, HyperCP reports a '*potential*' new neutral boson X^0 observed via $\Sigma^+ \rightarrow p X^0 \rightarrow p \mu^+ \mu^-$. They determined the following branching ratios:

$$Br(\Sigma^+ \rightarrow p \mu^+ \mu^-) = (8.6^{+6.6}_{-5.4}(stat) \pm 5.5(syst)) \times 10^{-8},$$

$$Br(\Sigma^+ \rightarrow p X^0 \rightarrow p \mu^+ \mu^-) = (3.1^{+2.4}_{-1.9}(stat) \pm 1.5(syst)) \times 10^{-8}$$

- Hyper CP gave the mass of the '*potential*' new boson X^0 as: $(214.3 \pm 0.5) MeV$
- two groups (Valencia *et al.* and Deshpande *et al.*) have recently computed $Br(K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-)$ in a phenomenological fashion.

Previous Studies

~Theorist Brainstorming~

- Valencia *et al.* and Deshpande *et al.* calculate $Br(K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-)$ following observations made by HyperCP; that is, they assume that the X^0 's have small widths, are short lived and do not interact strongly.
- Deshpande *et al.* estimates constraints on scalar and pseudoscalar X^0 's.
- finding that pseudoscalar couplings have the largest contribution, they evaluate the branching ratio as:

$$Br(K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-) = 8.02 \times 10^{-9} \quad (\text{Deshpande et al., 2005})$$

- Valencia *et al.* take things a step further and consider scalar, pseudoscalar, vector and axial vector particle possibilities for the X^0 state.
- the decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ places serious constraints on scalar and vector particle possibilities. The branching ratio for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ has been measured to be:

$$Br[K^+ \rightarrow \pi^+ \mu^+ \mu^-] = (8.1 \pm 1.4) \times 10^{-8} \quad (PDG, 2004)$$

- combining the upper result with constraints on scalar and vector couplings, Valencia *et al.* calculates theoretical upper limits on $Br(\Sigma^+ \rightarrow p X^0 \rightarrow p \mu^+ \mu^-)$:

$$Br(\Sigma^+ \rightarrow p X_s^0 \rightarrow p \mu^+ \mu^-) < 6 \times 10^{-11}, \quad Br(\Sigma^+ \rightarrow p X_v^0 \rightarrow p \mu^+ \mu^-) < 3 \times 10^{-11}$$

- the above upper limits effectively eliminate both scalar and vector particles as explanations of the HyperCP result.

- they then use existing constraints on pseudoscalar or axial vector X^0 's to predict the pseudoscalar and axial vector X^0 contributions to the $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ decay mode:

$$Br(K_L \rightarrow \pi^0 \pi^0 X_p^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-) = (8.3_{-6.6}^{+7.5}) \times 10^{-9}$$

(Valencia et al., 2005)

$$Br(K_L \rightarrow \pi^0 \pi^0 X_A^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-) = (1.0_{-0.8}^{+0.9}) \times 10^{-10}$$

- there is *no current experimental upper limit* on $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ or $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$.

The Possibility of $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Within The Standard Model

- the decay $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ is feasible within the Standard Model although its' phase space is limited to a paltry 16.35 MeV.
- although there is no current published Standard Model theory for $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$, Heiliger and Sehgal have paper out there on $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$.
- the amplitude of $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ is encompassed in a two piece set, with one piece coming from conversion of a virtual photon in the process $K_L \rightarrow \pi^0 \pi^0 \gamma^*$ and another with a real photon amplitude $K_L \rightarrow \pi^0 \pi^0 \gamma$.
- even in the narrow phase space of $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$, the direct γ^* production will only yield a background in the $\mu^+ \mu^-$ mass band around 214 MeV.

Previous KTeV Studies



- the data used in the previous KTeV study was from the 1997 E799 run.
- results from that analysis include:

~acceptance of 2.73% \rightarrow single event sensitivity of 1.4×10^{-10}

~signal of less than 2.3 events

~partial width for 'new physics' estimated to be $< 4.0 \times 10^{-24} MeV$

90% C.L. \downarrow

- the aforementioned analysis does however have some potential shortcomings that need to be addressed, such as the following:

~identification and estimation of background.

~selection and completion of a normalization analysis.

~systematics in the sensitivity!

~usage of a constant matrix element in the $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ MC generation.

Previous KTeV Studies

$(K_L \rightarrow \pi^0 \mu^+ \mu^-)$

- KTeV thesis on $K_L \rightarrow \pi^0 \mu^+ \mu^-$ was completed in early 1999.
- this decay is particularly interesting since it contains a direct CP violating contribution within the Standard Model.
- two events were observed with an expected background of events from MC simulation. The upper limit was set at: 0.87 ± 0.15
 $Br(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$ *←90% C.L.* $(PRL, June 2000)$
- the above analysis was performed on the KTeV E799 1997 data set only.
An analysis on the 1999 data set has yet to be performed.

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Analysis Strategy

-Data Selection-

- the data to be used in this study will be from the dimuon trigger of the 1997 (1999 later on) KTeV E799 run. The tapes used were NZL001-NZL130.
- a 'crunch' has been performed on these 130 data storage tapes...these tapes contained approximately *1.73 TeraBytes* of data. KteVana v6.04 was used on the crunch and KteVmc v6.04 was used for MC generation.
- some other decays available from the dimuon trigger are: $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$, $K_L \rightarrow \pi^0 \mu^+ \mu^-$, $K_L \rightarrow \mu^+ \mu^- \gamma\gamma$ and $K_L \rightarrow \mu^+ \mu^- \gamma$.
- two potential candidates for the *normalization* mode are $K_L \rightarrow \mu^+ \mu^- \gamma$ and $K_L \rightarrow \mu^+ \mu^- \gamma\gamma$.

$\text{TRIG5}[2\text{MU-LD}] =$

$\text{GATE} * 2V * \text{DC12} * 2\text{MU3} * \text{PHVBAR1} * 2\text{HCY_LOOSE} * \text{HCC_GE1}$

$\angle '97 \text{ def'n}$

$2V$ = 2 hits in V view and 1 hit in V' view OR 2 hits in V' and 1 hit in V.

$DC12$ = at least 1 DCOR hit in each view of DC1 and DC2.

2MU3 = 2 or more hits in the X and Y views of MU3.

PHVBAR1 : this is a veto on all RC's (except RC8), all SA's and the CIA. Specifically, this rejects events that deposit ≥ 500 MeV in the RC's and ≥ 400 MeV in the SA's and the CIA.

2HCY_LOOSE : 2+ hits in every y view of the drift chambers (by the hit counting module); however, a missing hit is allowed in the y view of chamber 1 OR chamber 2.

HCC_GE1 : ≥ 1 hardware cluster.

(logic symbols: $\&$ or $*$ = AND , $|$ or $+$ = OR , $!$ = NOT)

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Event Reconstruction

-Crunch Cuts-

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch Cut*	Data ♪	MC ♪	Data ♪	MC ♪	$K_L \rightarrow \pi^0 \mu^+ \mu^-$ Crunch Cut*
Require 2 tracks	0.700	0.992	0.700	0.996	Require 2 tracks
$C_{\text{track1}} = -C_{\text{track2}}$	0.999	1.000	0.999	1.000	$C_{\text{track1}} = -C_{\text{track2}}$
$E_{\text{cl}}(\text{track}) \leq 2.0 \text{ GeV}$	0.391	0.942	0.391	0.982	$E_{\text{cl}}(\text{track}) \leq 2.0 \text{ GeV}$
$E_{\text{cl}}(\text{track}) / p_{\text{track}} \leq 0.9$	0.999	1.000	0.999	1.000	$E_{\text{cl}}(\text{track}) / p_{\text{track}} \leq 0.9$
# γ clusters ≥ 4	0.056	0.629	0.366	0.720	# γ clusters ≥ 2
# hits in μ planes ≥ 1	0.980	1.000	0.982	1.000	# hits in μ planes ≥ 1
$ M_{\text{rec.pi0}} - M_{\text{pi0}} \leq 15 \text{ MeV}$	0.196	0.983	0.480	0.985	$ M_{\text{rec.pi0}} - M_{\text{pi0}} \leq 15 \text{ MeV}$
$90.0 \text{ m} \leq Z_{\text{VTX}} \leq 160.0 \text{ m}$	0.265	0.985	0.987	0.999	$90.0 \text{ m} \leq Z_{\text{VTX}} \leq 160.0 \text{ m}$
			0.887	0.997	$400 \text{ MeV} \leq K_{\gamma\gamma\mu\mu} \leq 600 \text{ MeV}$
$p_T^2 \leq 0.06 \text{ GeV}^2/c^2$	0.569	0.999	0.678	0.993	$p_T^2 \leq 0.0025 \text{ GeV}^2/c^2$
Total Acceptance/Rejection	0.00044	0.569	0.028	0.687	Total Acceptance/Rejection

* = cuts listed in chronological order, ♪ = initial # events was ~20K, ♫ = initial # events was ~277 M

-Notes on Crunch-

- Runs 10923-10928 (on Tape NZL118) and the last (and only) run on Tape NZL130 were *bad*. Upon submission, the following **Error/Abort** message was received:

BFRINGEINI: ERROR!!!

user wants FRINGEOPT = 7 (ktevana v6.04 default)

please set FRINGEOPT = -1

& try again.

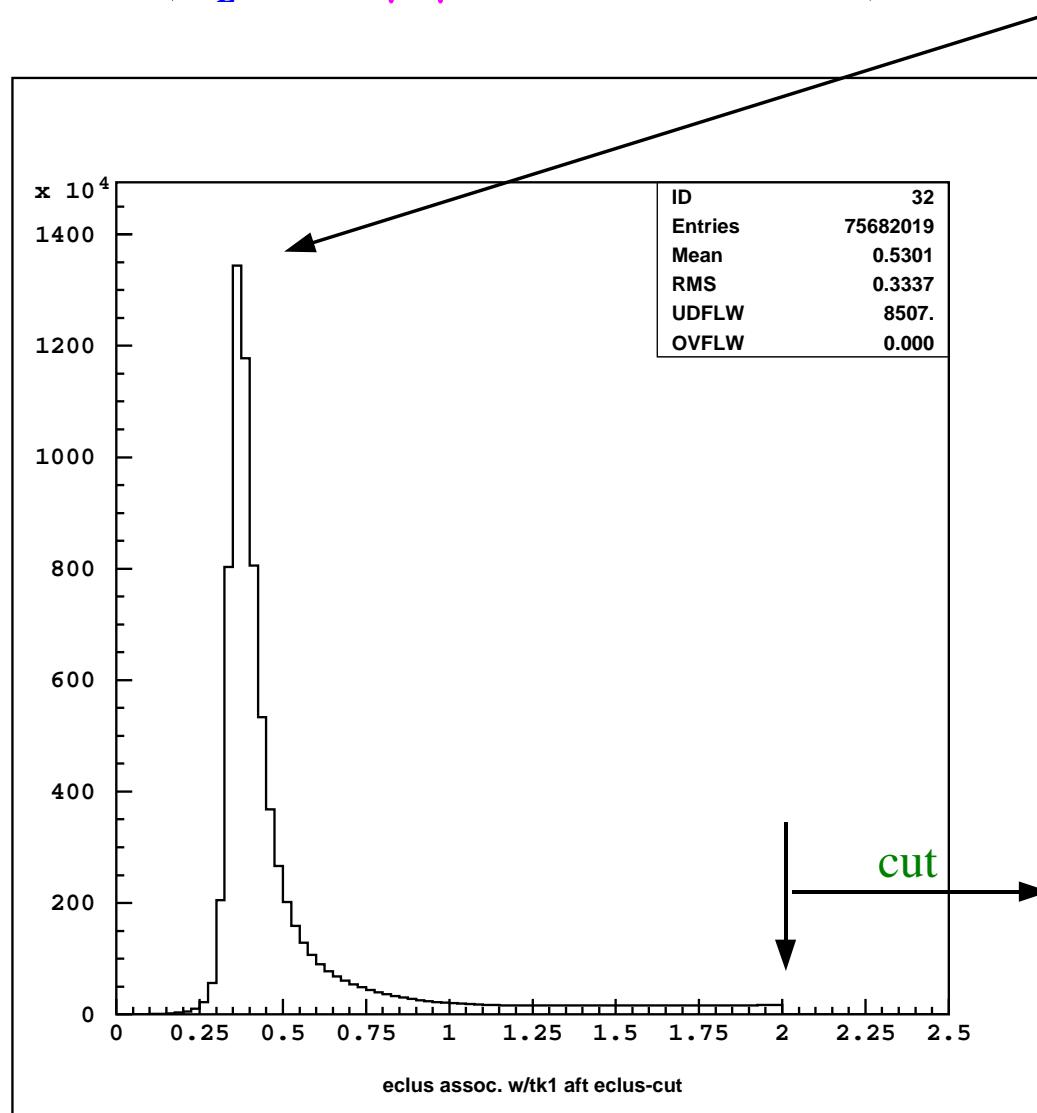
ABORT

- have refrained from crunching these runs altogether. This only yields a loss of about *0.4%* of the data.
- this change is also reflected in the .mrn file for MC generation.

Cut On E_{cl} Associated w/the Track

($K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch - 3rd Cut)

MIP Peak!

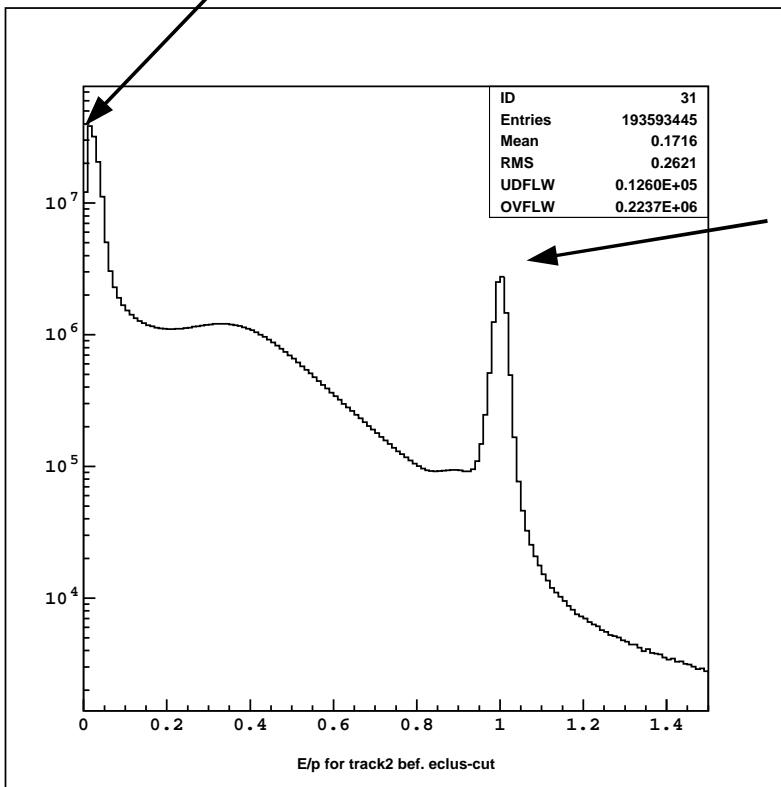


Data

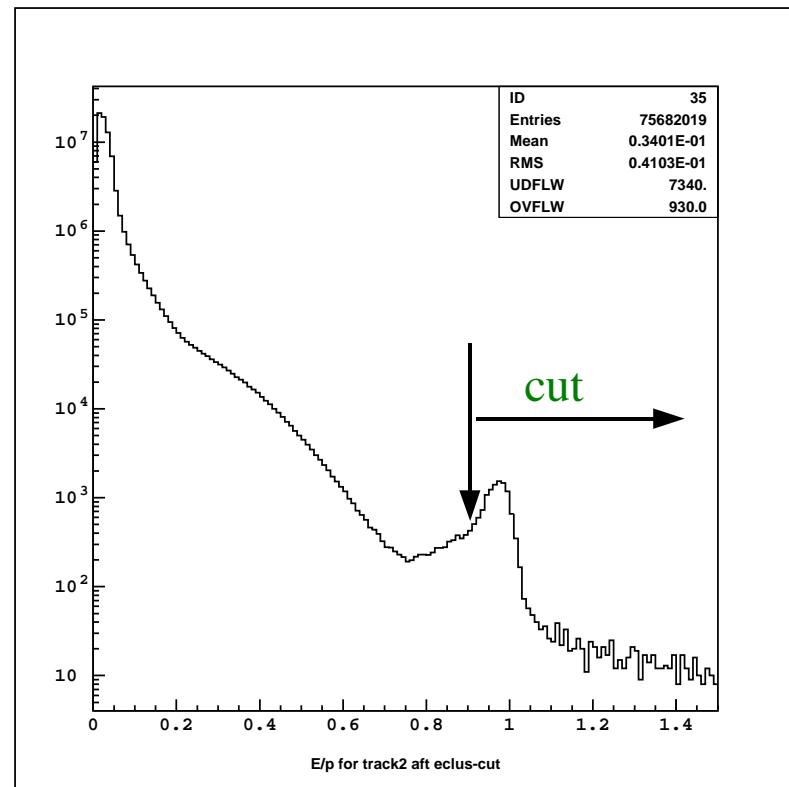
Cut On $E_{\text{cl}}(\text{track})/p_{\text{track}}$

$\mu \text{ peak}$

($K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch - 4th Cut)



$e \text{ peak}$



Data

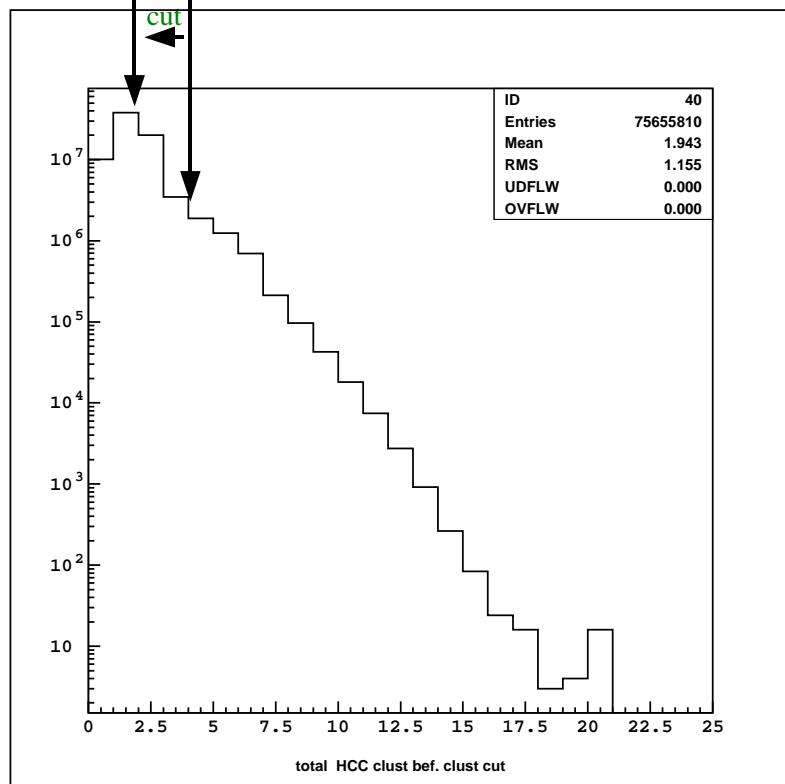
Data

Cut On Number of γ Clusters

$(K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-)$ Crunch - 5th Cut)

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$

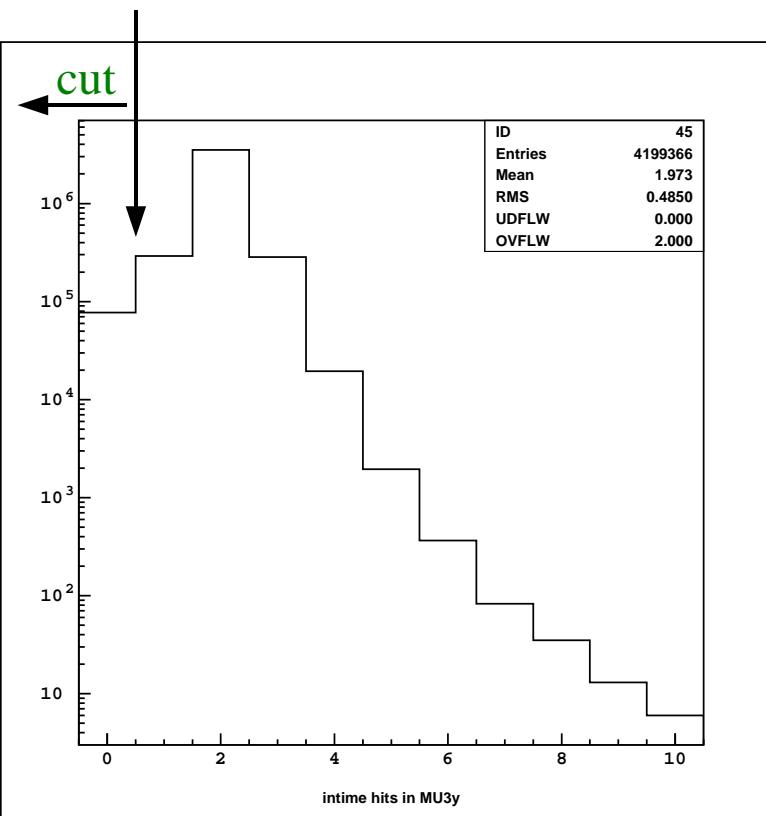
cut



Data

Cut On Number of Hits in μ Counting Planes

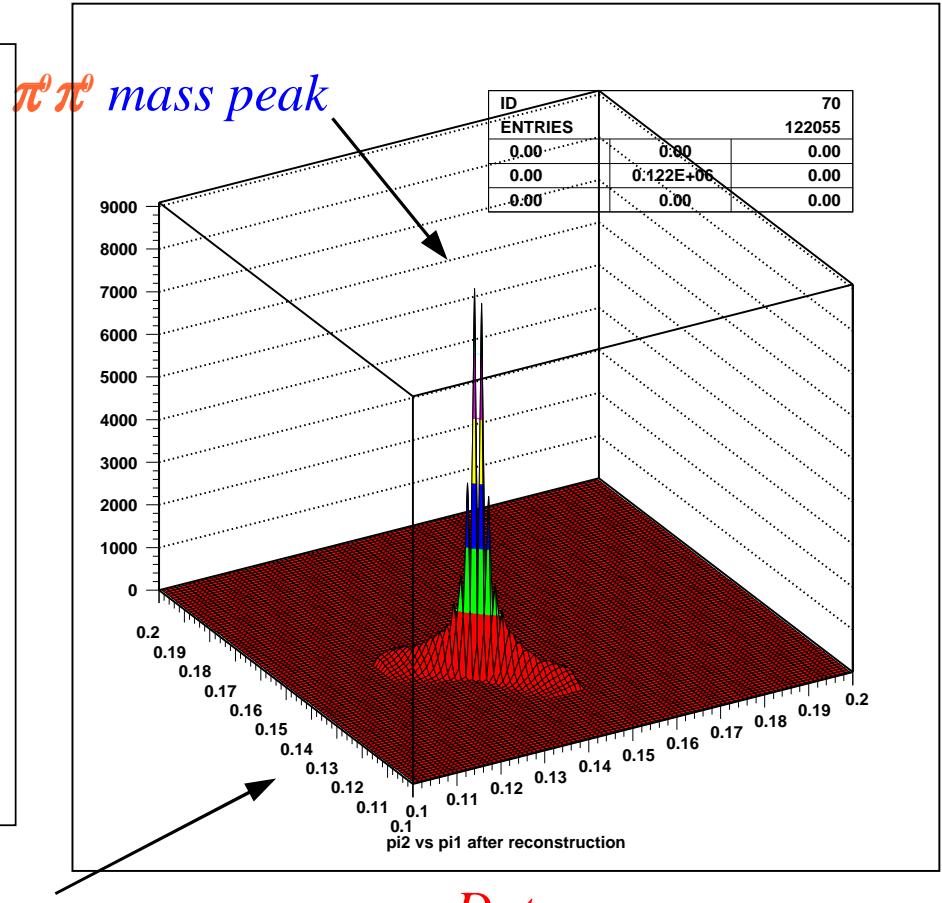
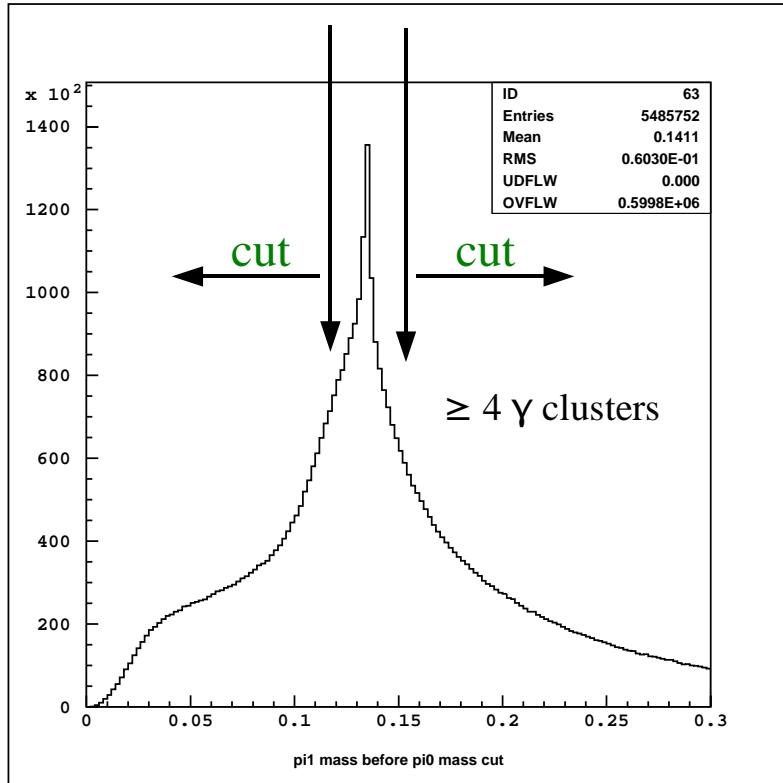
$(K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-)$ Crunch - 6th Cut)



Data

Cut On Reconstructed π^0 Mass

($K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch - 7th Cut)



Data

This mass peak could be from the following possible backgrounds:

Data

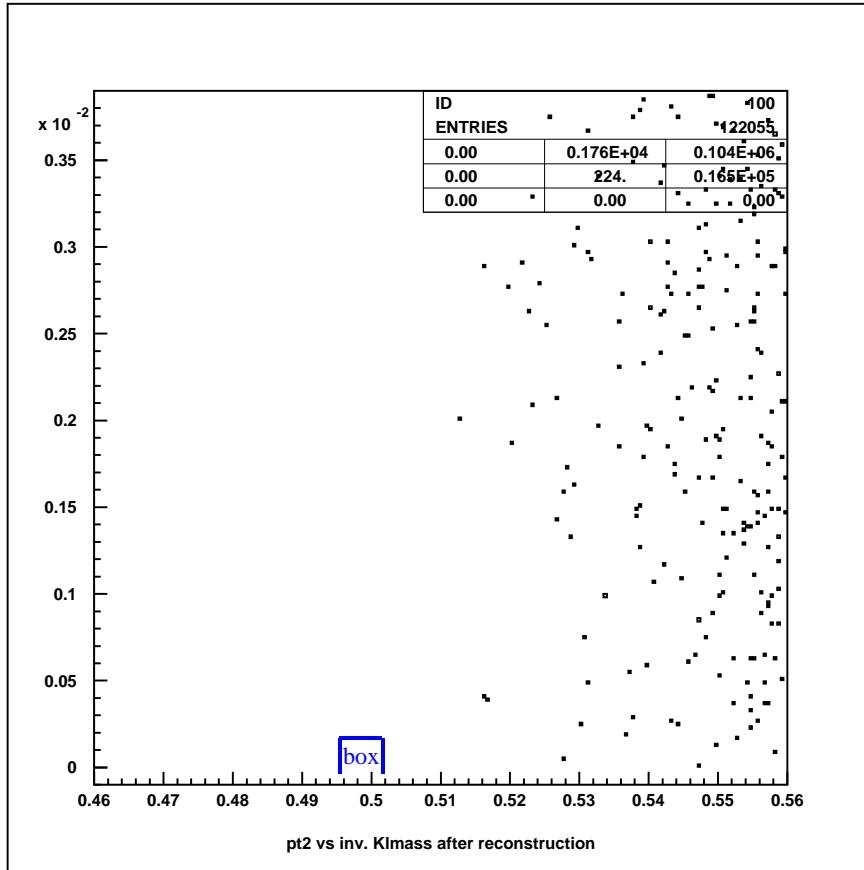
$K_L \rightarrow \pi^0 \pi^0 + acc.$

$K_L \rightarrow 3\pi^0$

$K_L \rightarrow 3\pi^0_D$

Results From Crunch of All Tapes

(P_T^2 vs. Inv. K_L Mass)

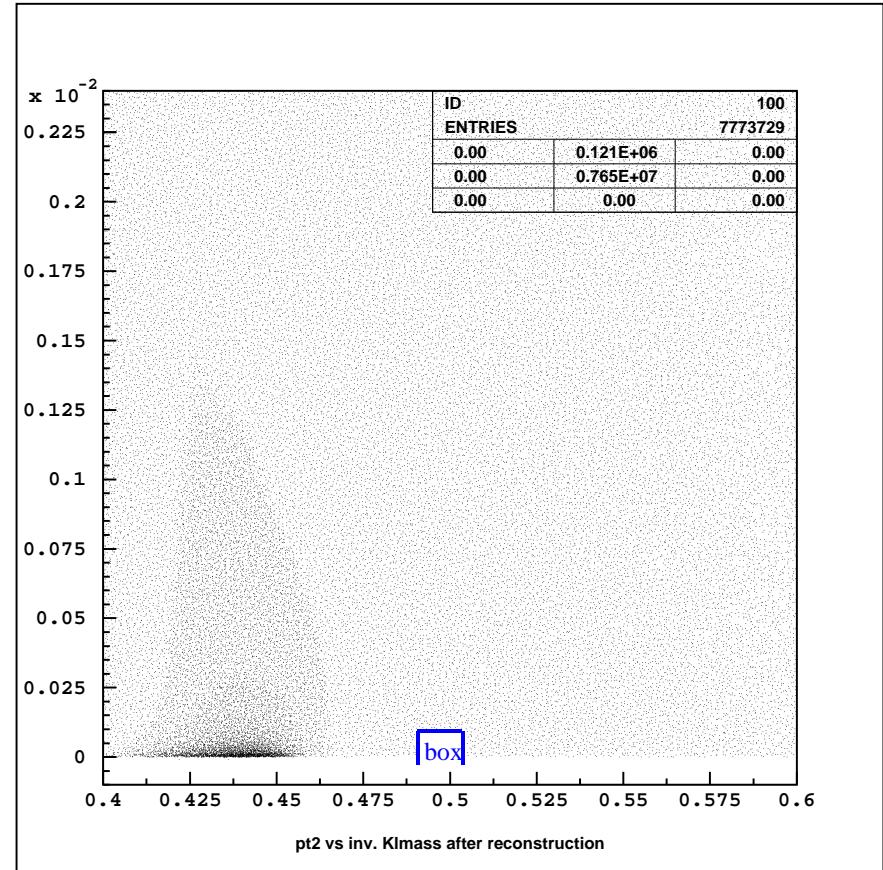


$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Data

~ Box Dimensions ~

$495 \text{ MeV} \leq M_{\gamma\gamma\gamma\mu\mu} \leq 501 \text{ MeV}$

$p_T^2 \leq 130 \text{ MeV}^2$

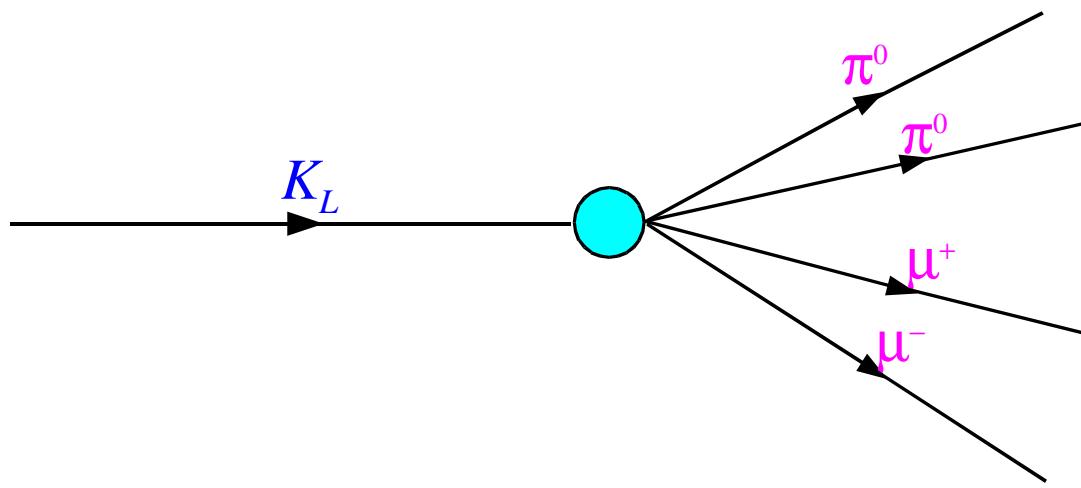


$K_L \rightarrow \pi^0 \mu^+ \mu^-$ Data

~ Box Dimensions ~

$491 \text{ MeV} \leq M_{\gamma\gamma\mu\mu} \leq 505 \text{ MeV}$

$p_T^2 \leq 100 \text{ MeV}^2$



$$P_{T,kaon}^2 = (\vec{P}_{T,\mu\mu vtx} + \vec{P}_{T,\pi 1} + \vec{P}_{T,\pi 2})^2, \text{ where } \vec{P}_{T,\mu\mu vtx},$$

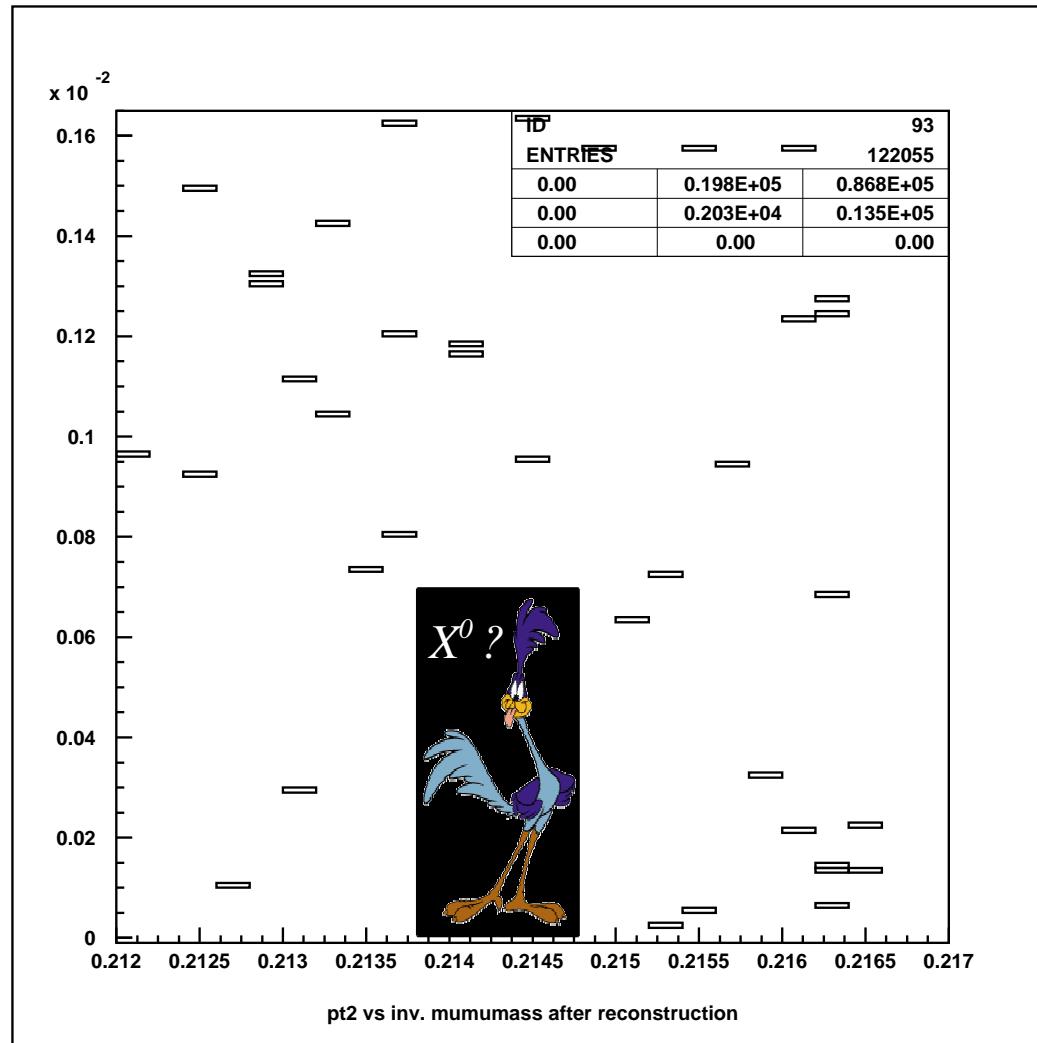
$\vec{P}_{T,\pi 1}$ and $\vec{P}_{T,\pi 2}$ are measured relative to the K_L direction.



$$P_{T,\mu\mu vtx}^2 - (\cancel{\vec{P}_{T,kaon}}^=0 - \vec{P}_{T,\pi 1} - \vec{P}_{T,\pi 2})^2 = 0, \text{ where } \vec{P}_{T,\mu\mu vtx},$$

$\vec{P}_{T,\pi 1}$ and $\vec{P}_{T,\pi 2}$ are measured relative to the K_L direction.

($[P_{T,\mu+\mu-vtx}^2 - P_{T,\pi^0\pi^0}^2]$ vs. Inv. $\mu^+\mu^-$ Mass)

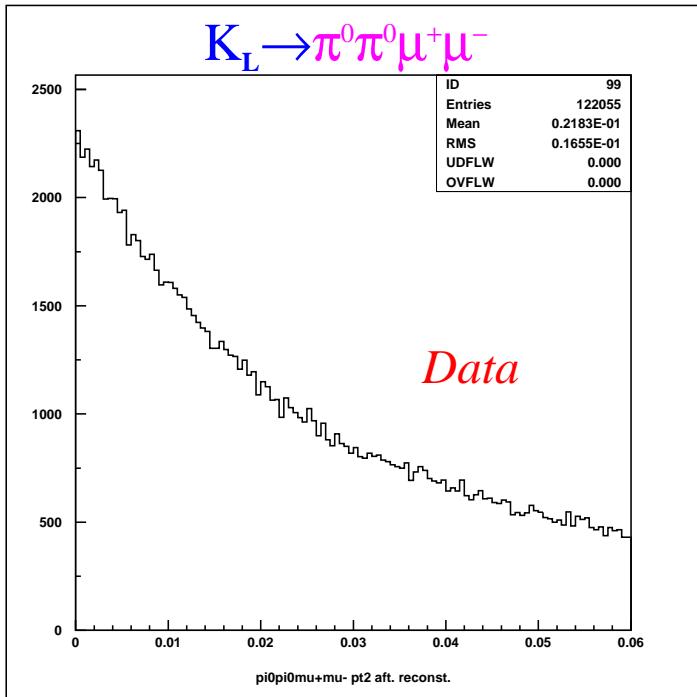


$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Data

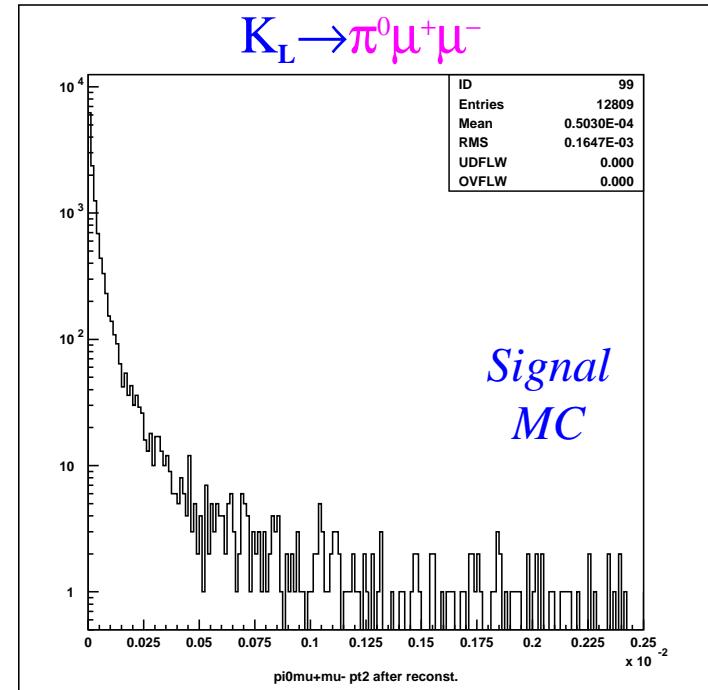
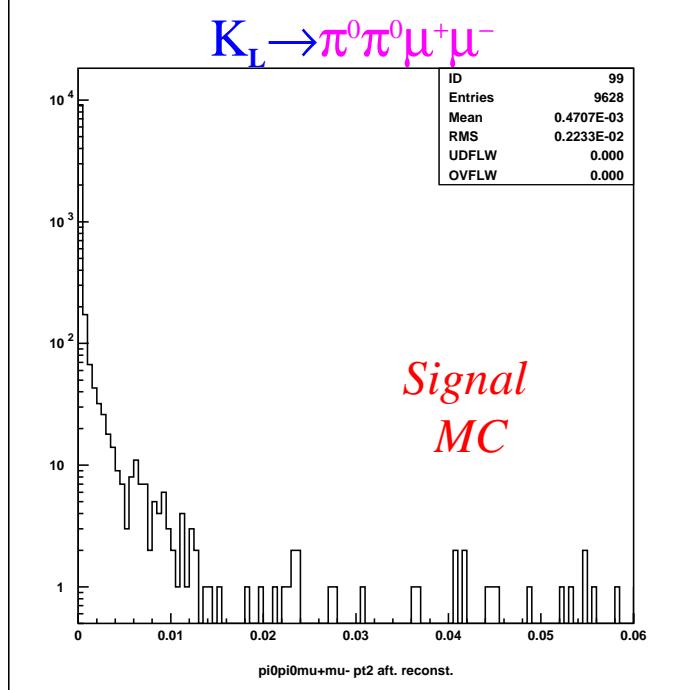
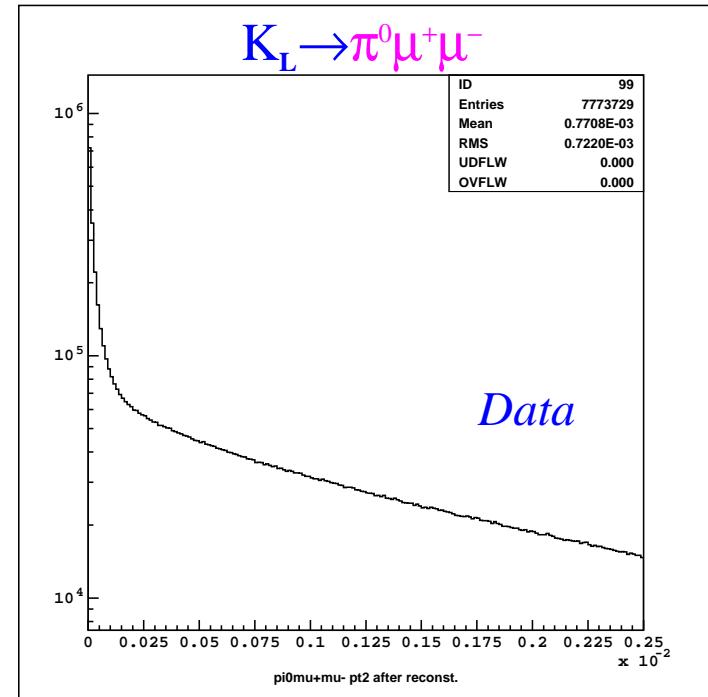
~ Box Dimensions ~

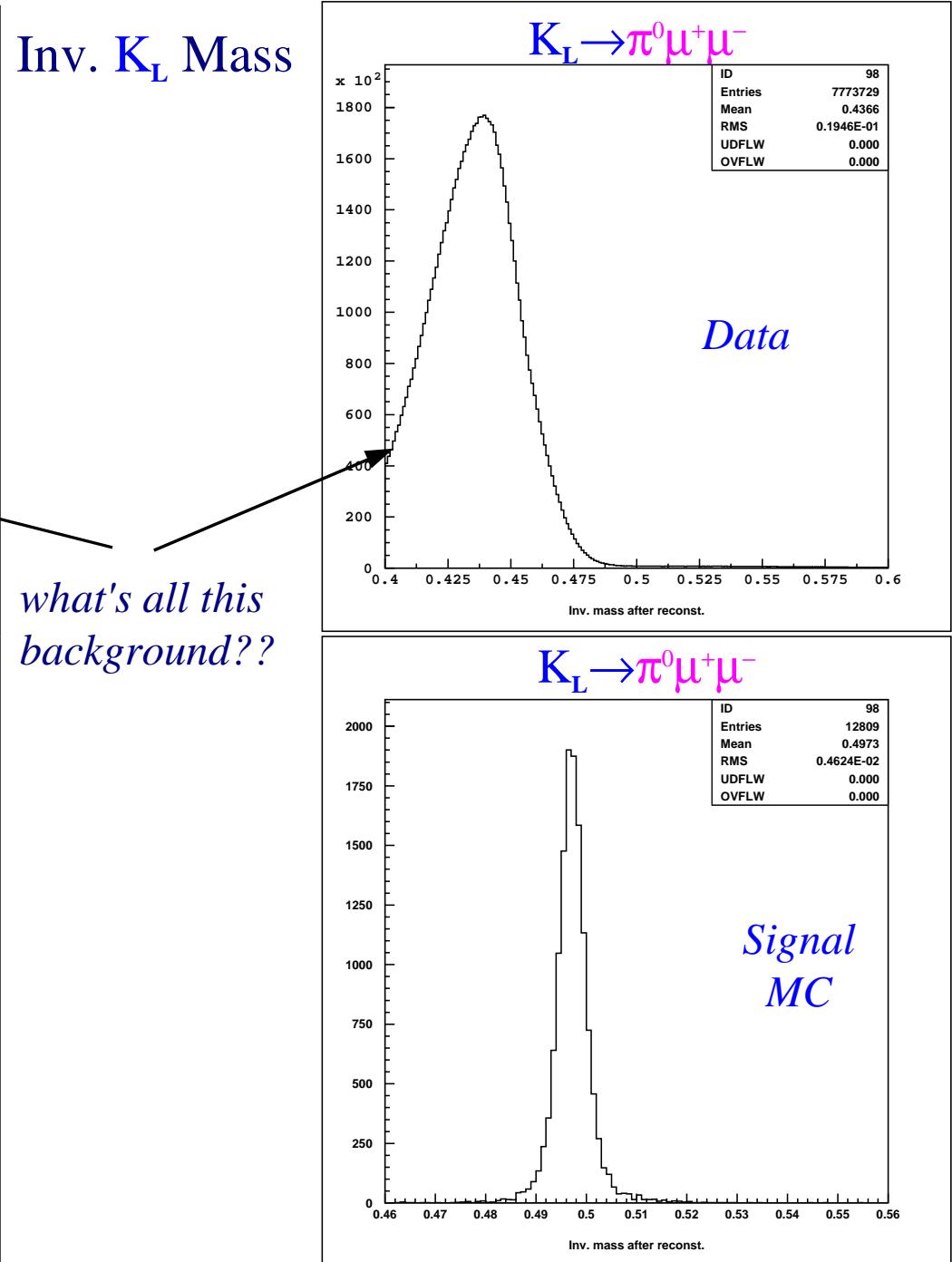
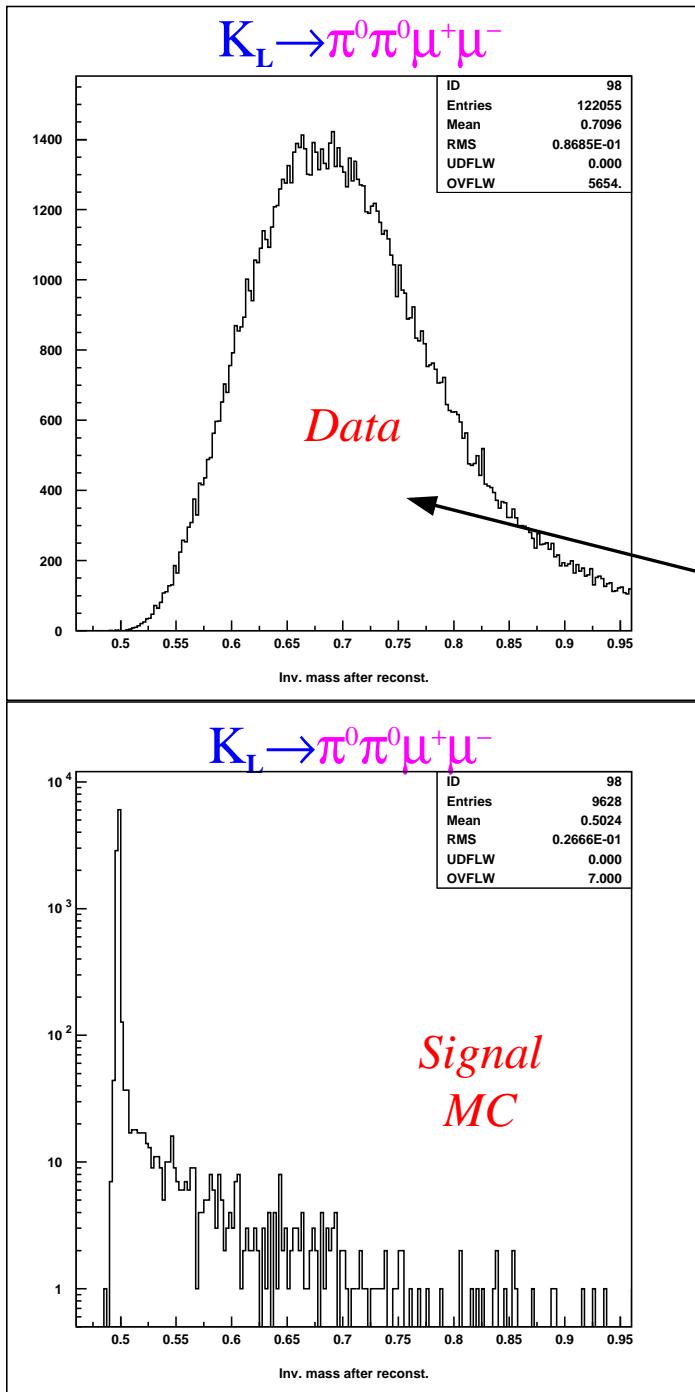
$213.8 \text{ MeV} \leq M_{\mu\mu} \leq 214.8 \text{ MeV}$

$p_T^2 \leq 700 \text{ MeV}^2$

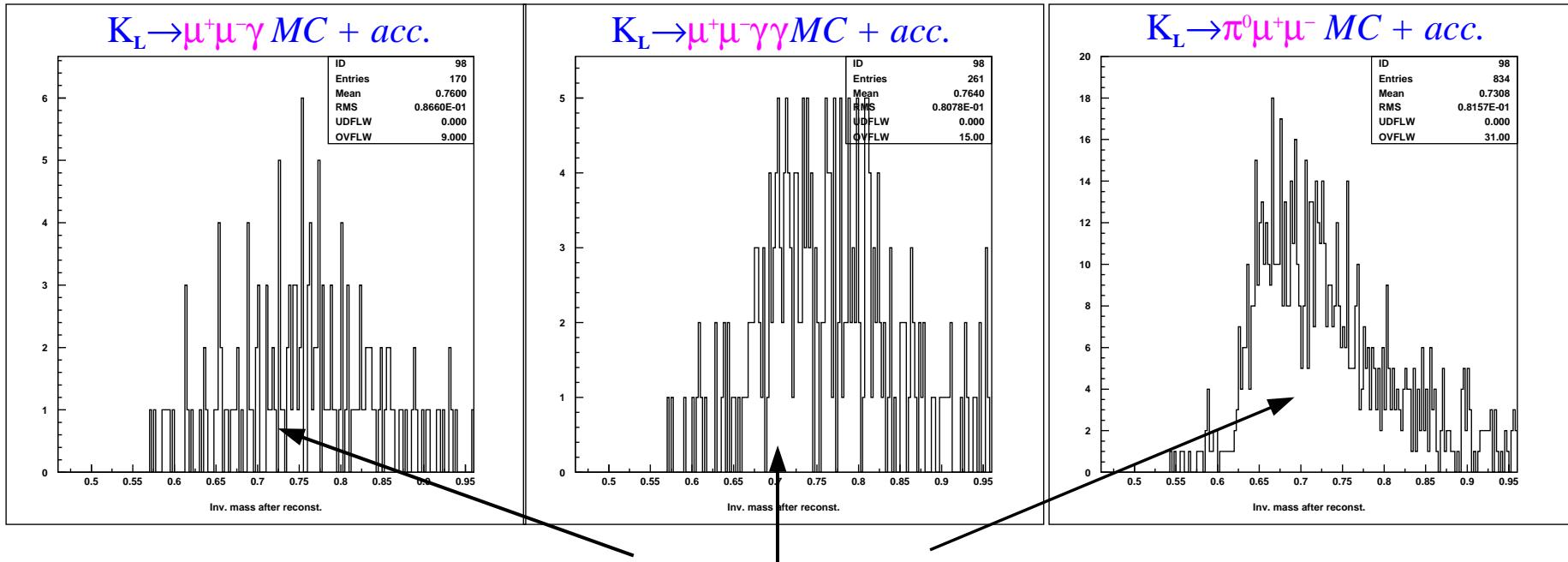


P_T²





MC Studies on High Mass Signal Mode Background



After feeding the above MC Samples (~2 M events) into the $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch Code, this is what we were left over with after all cuts.

- We can relate the above plots to the High Mass Background Spectrum in the Inv. K_L Mass Plot for $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ by extrapolation:
- 1265 events /(2 M MC events) ≈ x /(277 M Data events) → x ≈ 143578 background events
- So, our *MC Estimate* says that ~ 143578 events in the high mass signal mode background are due to the above three decays. This is within ~ 20 % of the true background.

Normalization Mode Studies**

-Crunch Cuts-

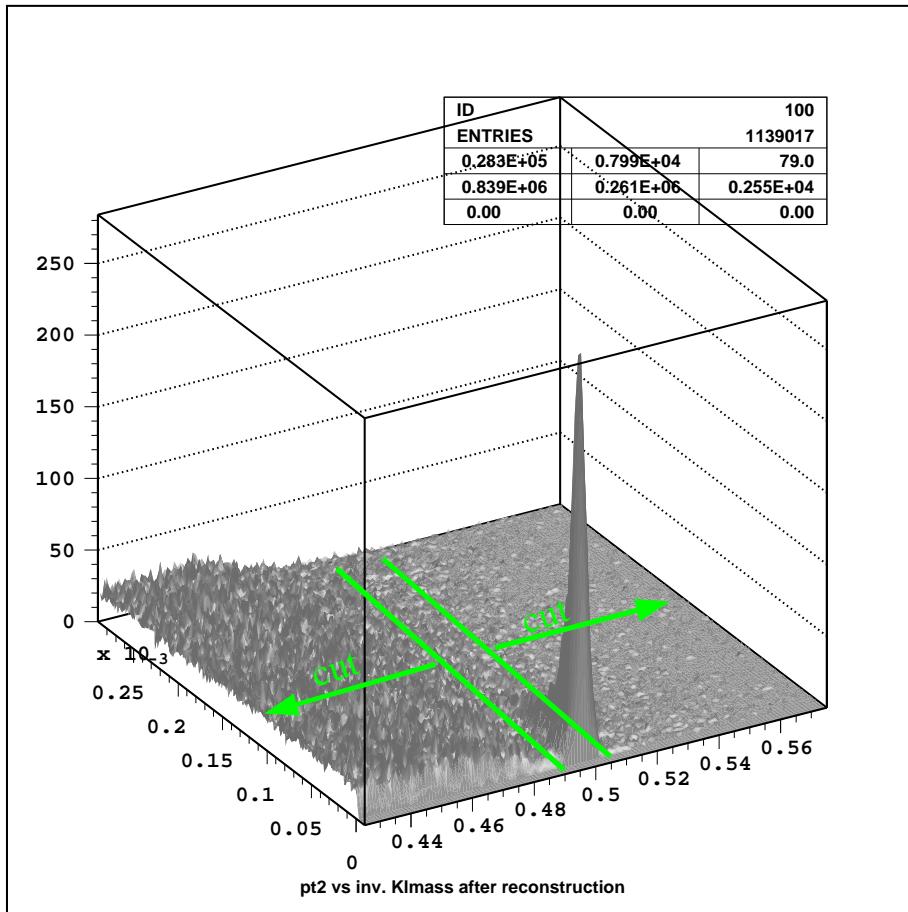
$K_L \rightarrow \mu^+ \mu^- \gamma\gamma$ Crunch Cut*	Data \downarrow	MC \downarrow	Data \downarrow	MC \downarrow	$K_L \rightarrow \mu^+ \mu^- \gamma$ Crunch Cut*
Require 2 tracks	0.700	0.998	0.700	0.998	Require 2 tracks
$C_{track1} = -C_{track2}$	0.999	1.000	0.999	1.000	$C_{track1} = -C_{track2}$
$E_{cl}(track) \leq 2.0 \text{ GeV}$	0.391	0.980	0.391	0.990	$E_{cl}(track) \leq 2.0 \text{ GeV}$
$E_{cl}(track) / p_{track} \leq 0.9$	0.999	1.000	0.999	1.000	$E_{cl}(track) / p_{track} \leq 0.9$
# γ clusters = 2	0.265	0.158	0.501	0.937	# γ clusters = 1
# hits in μ planes ≥ 1	0.983	1.000	0.988	1.000	# hits in μ planes ≥ 1
$90.0 \text{ m} \leq Z_{VTX} \leq 160.0 \text{ m}$	0.973	1.000	0.977	0.999	$90.0 \text{ m} \leq Z_{VTX} \leq 160.0 \text{ m}$
$p_T^2 \leq 0.0003 \text{ GeV}^2/c^2$	0.161	0.947	0.031	0.949	$p_T^2 \leq 0.0003 \text{ GeV}^2/c^2$
			0.025	0.917	$492 \text{ MeV} \leq K_{\mu\mu\gamma} \leq 504 \text{ MeV}$
Total Acceptance/Rejection	0.011	0.147	0.0001	0.806	Total Acceptance/Rejection

* = cuts listed in chronological order, \downarrow = initial # events was $\sim 20K$, \downarrow = initial # events was $\sim 277 M$

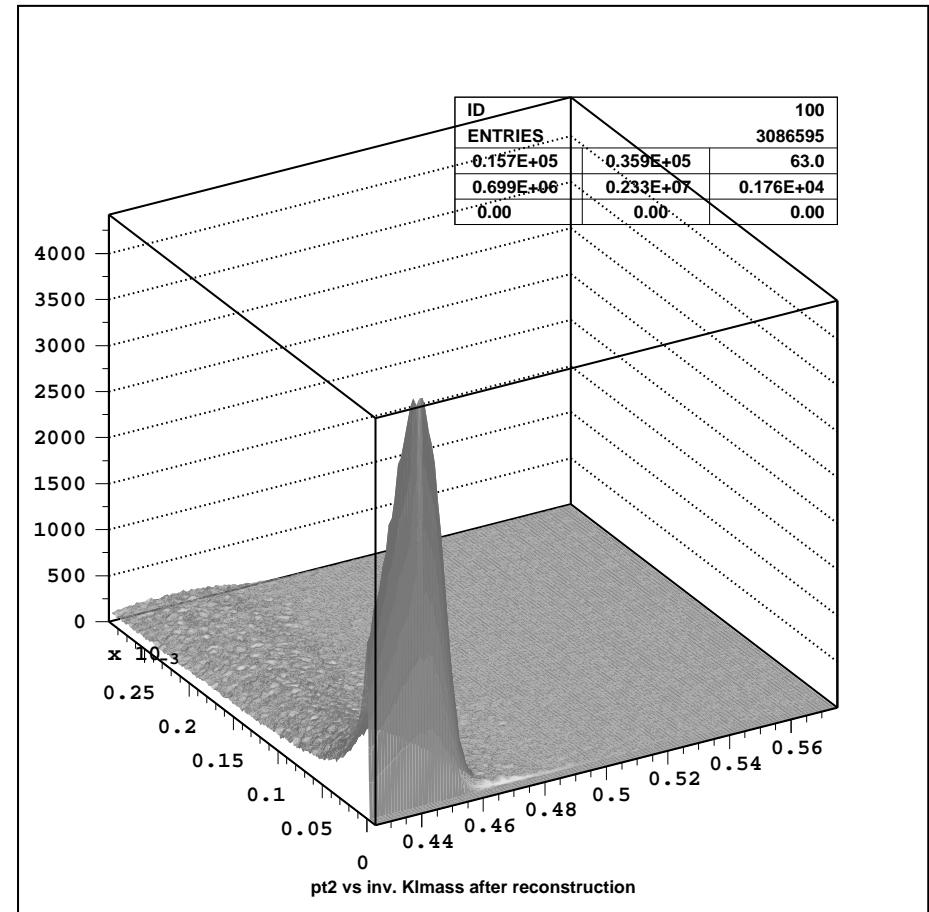
** = have not decided on a normalization mode yet

Normalization Modes:

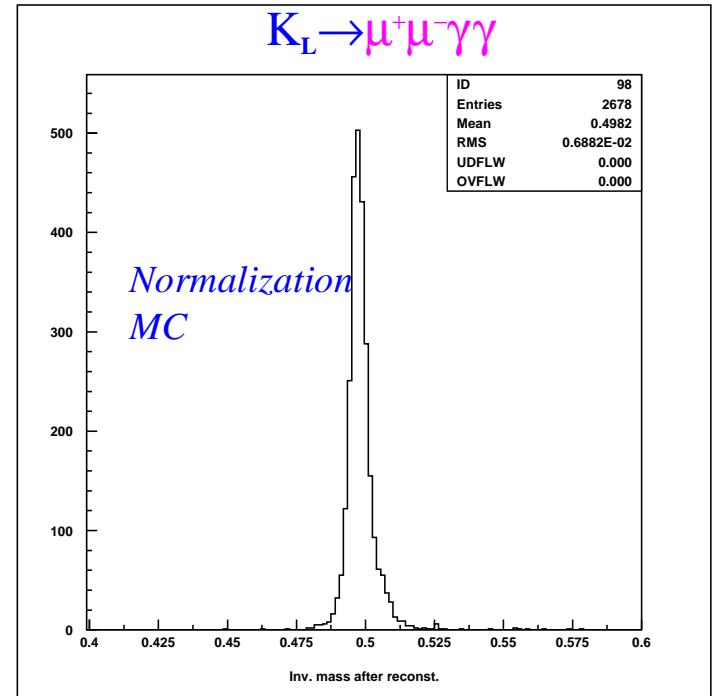
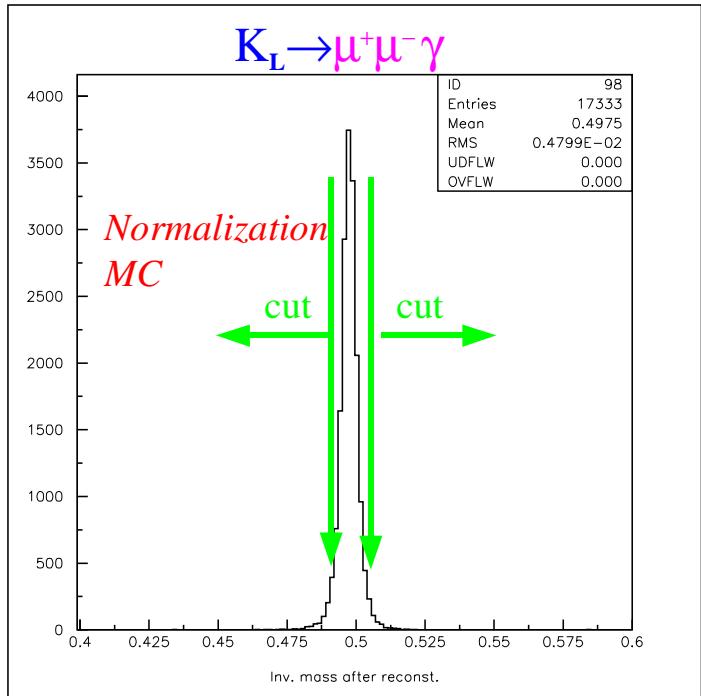
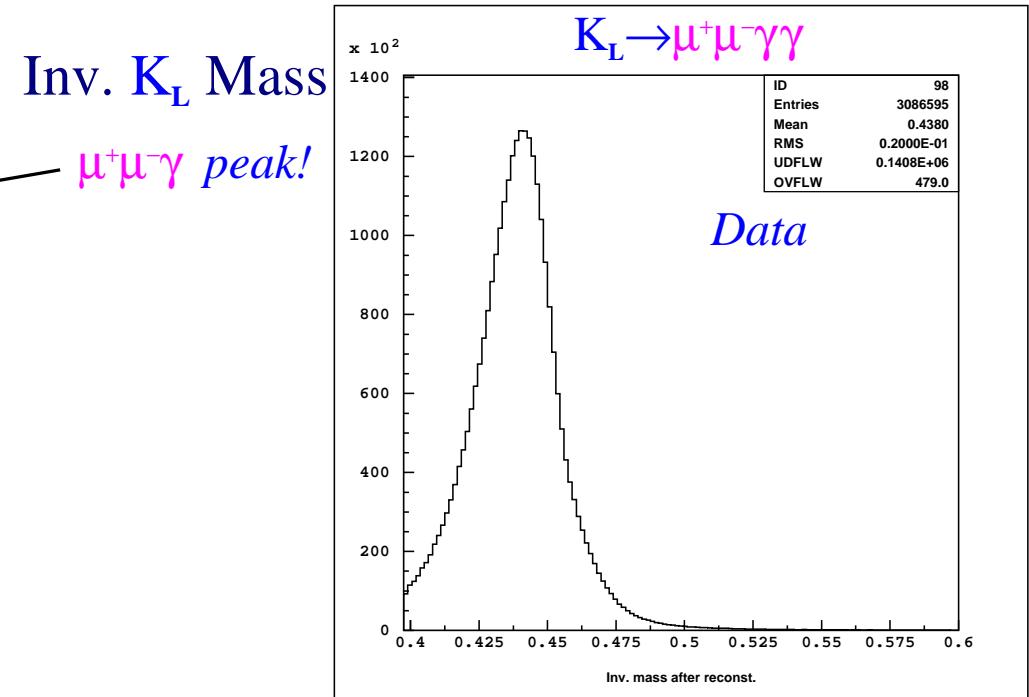
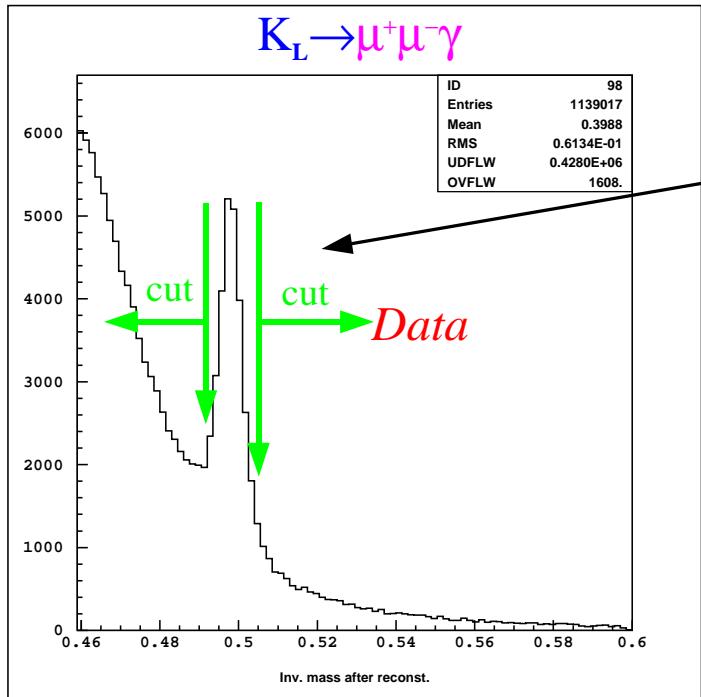
P_T^2 vs. Inv. K_L Mass

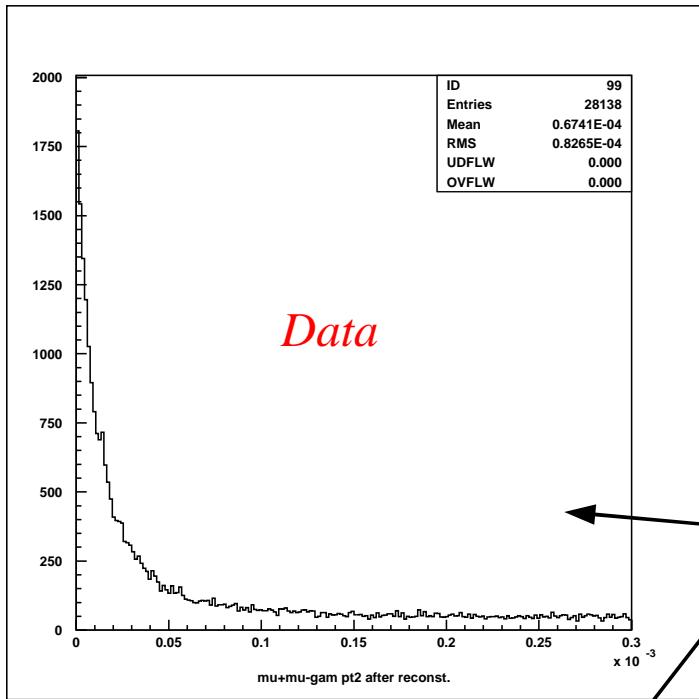


$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$ Data



$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$ Data

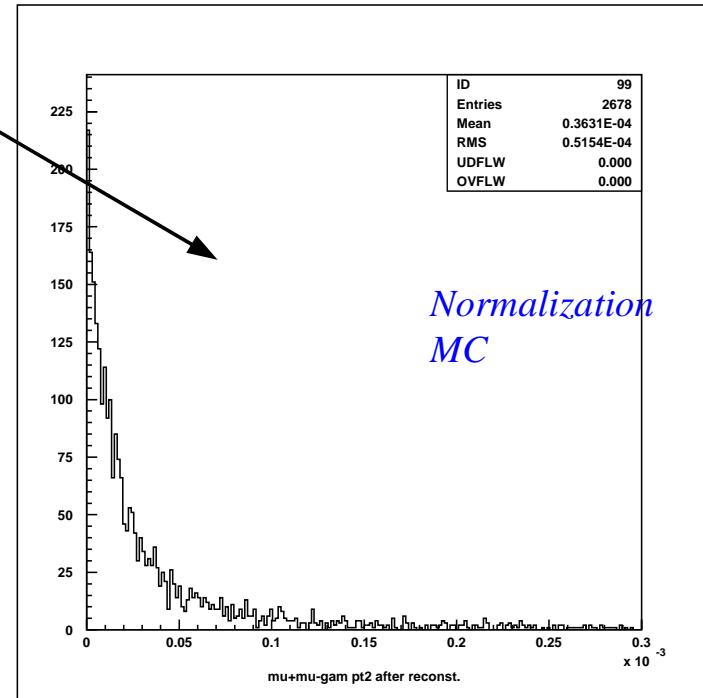
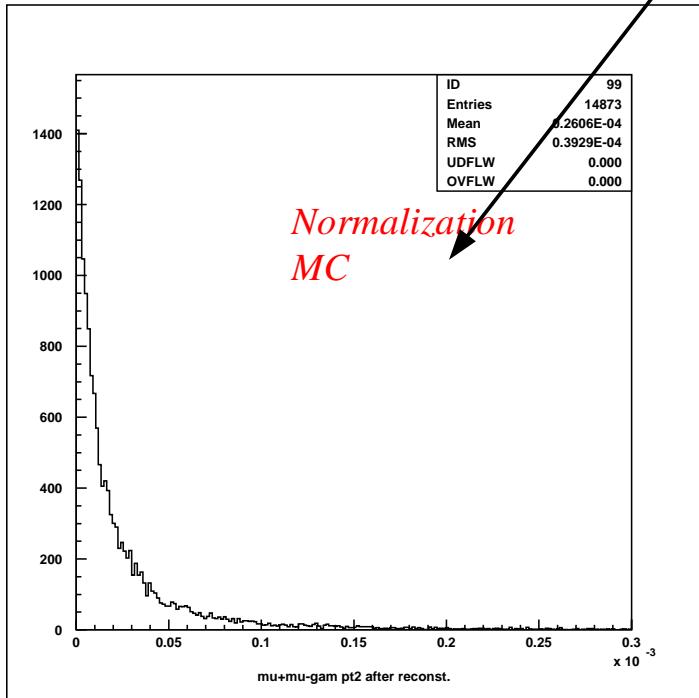
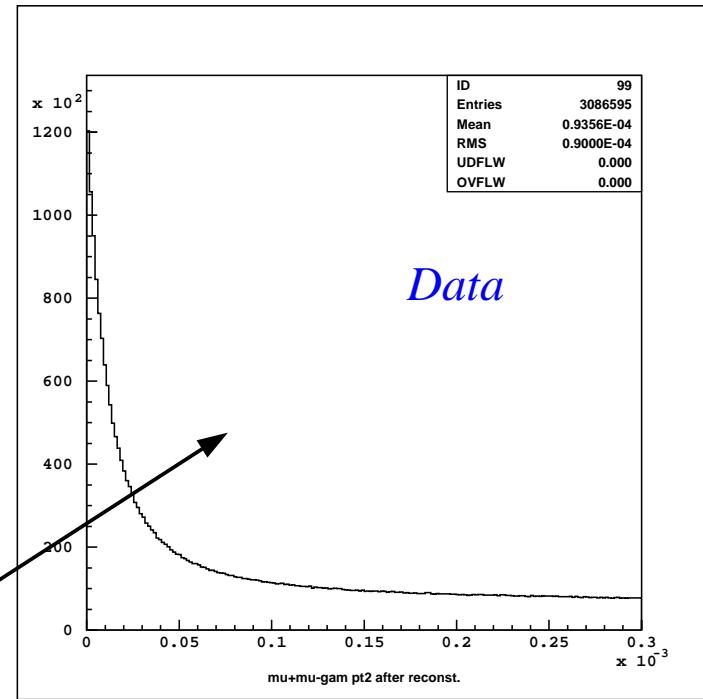




P_T^2

$K_L \rightarrow \mu^+ \mu^- \gamma$

$K_L \rightarrow \mu^+ \mu^- \gamma\gamma$



Future Plans

- HyperCP uses a uniform matrix element for $\Sigma^+ \rightarrow p X^0 \rightarrow p \mu^+ \mu^-$. This would not be advisable for $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ since the K_L decay is momentum dependent.
 - *must ensure that we use the **correct matrix element** in the MC generation!!!*
- luckily, *Deshpande et al.* gives the matrix element for $K_L \rightarrow \pi^+ \pi^- X^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ (albeit for a pseudoscalar X^0)
- meanwhile, *Valencia et al.* provides the matrix element for the decay $K^0 \bar{b} \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ (for both pseudoscalar and axial vector X^0 's)
- with the tools listed above, we should be able to construct a suitable matrix element for $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ and improve MC generation!

- in short, this analysis has been started from scratch and I will be analyzing the data *with the box closed* and with my own cuts.
- still need to decide on my *backgrounds*, which would reside at the edge of phase space.